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NAVAL AIR PROPULSION TEST CENTER

TRENTON, NEW JERSEY 08628

Aeronautical Turbine Department

NAPTC-ATD-152 July 1968

INVESTIGATION OF VITIATED INLET-AIR EFFECTS ON TURBOJET ENGINE PERFORMANCE

Independent Exploratory Development Project, IED-010

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1. Purpose. Enclosure (1) is forwarded for your information and retention.

2. Report Summary.

Laboratory tests were conducted to investigate the effects of vitiated inlet-air on turbojet engine performance. The test vehicle was a J60-P-6 turbojet engine which was operated at sea level hot day inlet conditions for simulated flight Mach numbers of 0.0, 0.5, and 0.85. Effects of vitiated inlet-air were evaluated at vitiation levels of 1.7, 2.3, 3.0, and 3.5 percent.

In general, inlet-air vitiation levels, up to 3.5%, created no measurable effects on engine performance.

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INTRODUCTION

As aircraft capabilities are expanded to include increased flight velocities, modern turbojet engines will encounter higher inlet-air temperatures. In addition, the demand continues for turbojet engines with increased thrust capability, which in turn necessitates increased engine air flow rates. To keep pace with these improvements, engine test facilities must be uprated to provide greater air heating capacities coupled with higher air heating temperatures.

Using conventional methods (steam or indirect fired heat exchangers) for heating air is expensive and equipment capabilities are not easily expanded to meet increasing requirements. A possible solution to this problem would be the use of vitiated air to attain high inlet-air temperatures and/or to provide additional air heating capacity. In this case, preliminary estimates indicate equipment costs are low relative to the cost of heat exchangers and the system design is flexible, thereby permitting economical future expansion. Furthermore, space requirements are low and existing air heating systems can be augmented readily using the vitiated air heating method.

Vitiated air is defined as follows:

> "...vitiated air has an oxygen content which is less than that of ordinary air. For example, air containing a diluent such as nitrogen or argon is vitiated; again, air contaminated by the products of a previous combustion process within it is vitiated."(1)[1]

For the purpose of this investigation, though, vitiated air will be defined as having a reduced oxygen content as a result of mixing pure air with hot combustion products.

The issue to be resolved, however, is: does the use of vitiated inlet-air have an effect on turbojet engine performance and if so, can this effect be predicted?

Review of current literature and discussions with industry regarding the use of vitiated air for high temperature air testing revealed the following:

1. Literature is available which discusses the effects of vitiated air on the combustion process; however, published information treating the effects of vitiation on overall turbojet engine performance could not be located.

2. A few industrial organizations use vitiation as a means of determining the effect of high temperature operation on various engine component parts.

3. Pratt and Whitney Aircraft Corporation and Marquardt Corporation have used vitiated air for developmental tests of turbojet and ram jet engines; however data relating to the effects of vitiation on performance was not formally distributed.

Since adequate information regarding the use of vitiated air for turbojet engine testing was not available, the Naval Air Propulsion Test Center (NAPTC) established an Independent Exploratory Development Project to investigate these effects. The scope of this investigation, however, is limited to the effects of vitiated inlet air on turbojet engine performance at sea level inlet conditions.

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[1]Numbers in parentheses designate cited references listed on page 27

SUMMARY

The purpose of this investigation was to study and determine the feasibility of using vitiated inlet air in conjunction with gas turbine power plant testing. Specifically, the following objectives were pursued:

1. To determine the effects of vitiated air on the performance of a gas turbine power plant.

2. To establish allowable air vitiation limits for gas turbine power plant testing.

3. To develop methods for predicting performance effects and/or correcting test data when vitiated inlet-air is used.

A turbojet engine was installed in a specially configured test cell which permitted operation with either pure or vitiated air under identical engine inlet conditions. Test data was obtained at vitiation levels up to 3.5%.

A theoretical thermodynamic cycle analysis to predict vitiation effects is being developed and an attempt will be made to compare predicted and actual engine performance effects. The theoretical analysis of vitiation effects, however, will be the subject of a future discussion and/or report.

CONCLUSIONS

Sea level testing of a Pratt and Whitney J60 Turbojet Engine indicates that vitiation levels up to 3.5% reduction in inlet-air oxygen content have little or no measurable effect on engine performance.

Limitations of the air heating equipment employed for this investigation precluded the establishment of a maximum acceptable percent vitiation for sea level turbojet engine performance testing.

In general, vitiation effects will be more noticeable as combustion pressures are reduced; i.e., as altitude is increased and/or flight velocity is decreased.(2)

RECOMMENDATIONS

1. The effects of vitiated inlet-air on overall engine performance should be investigated under altitude test conditions.

2. A detailed investigation of the combined effects of reduced pressure and air vitiation on the combustion process should be performed to permit accurate prediction of and correction for vitiated inlet-air effects.

APPARATUS AND PROCEDURE

Description of Equipment

The test facility is depicted schematically in Figure 1. Pure air was introduced via the normal test cell inlet-air supply system. This system includes provisions for controlling inlet-air pressure and temperature. The inlet-air heat exchanger is capable of both cooling to -65°F and heating to 250°F. To this system

was added a source of highly vitiated air in the form of combustion products from a direct combustion air heater (pictured in Figure 2). These gases were mixed with the pure air to produce the required inlet-air temperature at the desired level of vitiation. In this case, engine inlet-air temperature was regulated by the vitiated air temperature control valve and the vitiation level was established by heating or cooling the pure air flow. The method for determining the vitiation level is presented in Appendix B. A uniformly mixed flow at the engine bellmouth was ensured by the use of a long mixing duct (L/D=20) which included a coarse conical shaped screen at its mid-point. The screen also served as a precaution against foreign object damage to the engine resulting from the possible breakdown of the air heater combustion chamber liner.

Figure 3 illustrates the Pratt and Whitney J60 Turbojet Engine installation in the NAPTC 3W Test Cell. The J60 Engine was selected for this investigation because of its straight forward design, fixed compressor stators, single spool and fixed area nozzle, which permitted simplified analysis of vitiation effects. Also, its relatively small air flow requirements permitted use of an existing combustion air heater.

Instrumentation

The instrumentation configuration used for obtaining facility and engine performance data is illustrated diagrammatically in Figure 4. The range, accuracy and type of each recorded data parameter are shown in Table I (page 15). A direct reading oscillographic record of selected engine parameters was made during each test run to ensure steady-state conditions were established and as a "back-up" acquisition system for essential engine performance data. The range, accuracy and type of each oscillographic data channel are shown in Table II (page 17).

All test data were obtained during steady-state engine operating conditions. Pressures were measured with either mercury filled manometers or with Kollsman gages if the pressure would exceed 30 psia. Thermocouples were employed for all temperature measurements. The standard engine harness was used to measure turbine discharge temperature. Temperatures were recorded from direct reading Precision Indicators referenced to either 32°F or 1200°F as appropriate. The engine and air heater fuel flows were measured with turbine-type flowmeters which were calibrated over a range of fuel temperatures anticipated during the test. Engine speed (rpm) was measured with a pulse generator mounted on the accessory gearbox. Flowmeter and pulse generator outputs, in cycles per second, were indicated on electronic digital counters.

A gross thrust measuring system was not available in the test cell utilized for this study. Therefore, the evaluation of the effects of vitiation on actual turbojet engine thrust was not possible. Attempts were made to calculate gross thrust from basic engine design and performance data. However, the results were deemed unsatisfactory since the calculations magnified small instrumentation deviations to such an extent that analysis was not practical.

Method of Test

The engine inlet temperature was regulated by the procedure discussed under Description of Equipment (page 2) and four levels of vitiation (0% - 3.5%) were established for each of three flight Mach numbers at sea level, hot day conditions. Data points were taken as rpm was set at 70%, 80%, 85%, 90%, 95% and 100% for each of these inlet conditions. Pure air, or 0% vitiation, runs were accomplished first to establish control or base-line data from which to evaluate the effects of vitiation. A test data and run index is presented in Table III (page 18).

RESULTS AND DISCUSSION

Data which illustrates the effect of vitiation on various turbojet engine operating parameters is displayed graphically in Figures 5, 6, 7 and 8. Each figure is a compilation of data taken at three simulated flight velocities (M_o = 0.0, 0.5 and 0.85) for sea level hot day inlet conditions under varying levels of air vitiation. The individual curves, which represent 0% vitiation engine performance, are terminated at the 100% speed point on the high rpm end and at the bleed valve actuation speed on the low rpm end. The low speed limitation was deemed necessary due to wide fluctuations in the steady state data when the compressor bleed valve opened.

A confidence band, for any given data point, is indicated in the lower right portion of each figure. This band was determined from the measurement accuracy for each parameter and it is used to realistically evaluate the effects of inlet air vitiation relative to instrumentation capabilities and graph scaling factors.

Analysis of Figures 5 through 8 demonstrates the negligible effect of inlet-air vitiation up to 3.5% on sea level turbojet engine performance. In general, all data points fall within the respective confidence bands and no significant trends or changes are noted. Figure 7 shows a slight indication of a change in fuel control parameter at the higher (3.0%-3.5%) vitiation levels; however, the trend is not consistant and the data points are still within the confidence band for 0% vitiation data.

Visual observation of the engine during the test program revealed no noticeable physical effects of vitiation on engine operation. Three vibration sensors were monitored continuously and no characteristic changes were noted. Post-test inspection revealed a thin coating or deposit on the engine inlet bullet-nose, inlet guide vanes and first stage compressor blades. The deposit was light brown in color and was evidently formed from condensing by-products of the combustion air heater. This was the most detrimental effect of vitiation observed during the test program. Selection of "cleaner" fuels (hydrogen, methane, etc.) for air heating would correct this problem area.

APPENDIX A

LIST OF SYMBOLS

Symbol	Definition	Units
N	Engine Rotor Rotational Speed	RPM
P_s	Stream Static Pressure	"HgA
P_t	Stream Total Pressure	"HgA
PLP	Power Lever Position	Degrees
T_t	Stream Total Temperature	°F
T_f	Fuel Temperature	°F
W_a	Air Flow	pounds/second
W_f	Fuel Flow	pounds/hour
$W_{(O_2)}$	Oxygen Weight Flow	pounds/second
h	Enthalpy	BTU's/pound
H	Enthalpy	BTU's/pound-mole
LHV	Lower Heating Value of Fuel	BTU's/pound
F/A	Fuel Air Ratio	pounds fuel/pound air
M.W.	Molecular Weight	--
C_p	Specific Heat at Constant Pressure	BTU/pound/°F
% VIT	Percent Vitiation	percent
δ	Ratio of Total Pressure to Standard Sea Level Pressure	--
θ	Ratio of Total Temperature to Standard Sea Level Temperature (in degrees Rankine)	--

Subscripts

1 - 9	Numbered subscripts refer to instrumentation stations as defined in Figure 4.
BI, BD, BO, C	Facility stations as defined in Figure 4.
E	Indicates an Engine Parameter
B	Indicates a Burner or Air Heater Parameter

APPENDIX A (Cont'd)

Subscripts	Definition
(200)	Refers to Conditions With Combustion in 200% of Theoretical Air
(400)	Refers to Conditions With Combustion in 400% of Theoretical Air

APPENDIX B - METHODS FOR CALCULATING LEVEL OF VITIATION

APPROXIMATION METHOD FOR CALCULATING TOTAL AIR FLOW THROUGH THE DIRECT COMBUSTION AIR HEATER

The enthalpy of the combustion products, in BTU's/Lb of gas leaving the burner, is determined from the expression:

$$h_{BO} = h_{BI} + (LHV)\left(\frac{W_f}{W_f + W_a}\right) \tag{1}$$

Where (LHV) represents the lower heating value of the fuel in BTU/Lb. Since enthalpy for products of combustion is expressed in BTU's/Lb-Mole (H_{BO}) in Keenan and Kaye(3); $(h_{BO}) = \frac{H_{BO}}{(M.W.)}$ or, from equation (1):

$$h_{BO} = \frac{H_{BO}}{(M.W.)} = h_{BI} + (LHV)\left(\frac{W_f}{W_f + W_a}\right) \tag{2}$$

Solving equation (2) for air flow (W_a) yields:

$$W_a = \frac{(LHV)\ W_f}{\frac{H_{BO}}{M.W.} - h_{BI}} - W_f \tag{3}$$

An expression for fuel-air ratio is then derived from (3):

$$\frac{W_f}{W_a} = \frac{1}{\left[\frac{(LHV)}{\left(\frac{H_{BO}}{M.W.} - h_{BI}\right)} - 1\right]} \tag{4}$$

The percentage of theoretical air (% air) used in the combustion process is obtained by dividing the stoichiometric fuel-air ratio by the actual fuel-air ratio.

$$\%\ air = \frac{F/A\ stoic.}{W_f/W_a} \times 100 \tag{5}$$

Or, by substituting equation (4) for W_f/W_a in equation (5):

$$\%\ air = \left[\frac{(F/A\ stoic.)\ (LHV)}{\left(\frac{H_{BO}}{M.W.} - h_{BI}\right)} - F/A\ stoic.\right] \times 100 \tag{6}$$

APPENDIX B (Cont'd)

For the burner system under consideration, the following data are known:

T_{BI}, T_{BO}, W_{fB}, Fuel = JP4R

And the following assumptions are made:

1. Combustion efficiency = 100%

2. Molecular weight of combustion products varies linearly with percent theoretical air over the range from 200% to 400%.

3. Enthalpy of the combustion products at a given temperature varies linearly with percent theoretical air.

Using Keenan and Kaye(3) and the above data and assumptions, the following relationships can be developed:

<u>Molecular Weight for Products of Combustion of JP4R Fuel for Any Percent Theoretical Air.</u>

$$M.\ W._x = M\ W_{(400)} + \left[\frac{M.W._{(400)} - M.W._{(200)}}{200}\right] (\%\ AIR_x - 400)$$

or:

$$M.\ W._x = 28.924 + 0.000075\ (\%\ AIR_x) \tag{7}$$

Where (x) denotes the value for a given % air.

<u>Enthalpy for Products of Combustion of JP4R Fuel at a Given Temperature for Any Percent Theoretical Air.</u>

$$H_{BO_x} = H_{BO\ (400)} - \left[\frac{H_{BO\ (200)} - H_{BO(400)}}{200}\right] (\%\ AIR_x - 400) \tag{8}$$

Values for $H_{BO(400)}$ and $H_{BO(200)}$ are obtained from Keenan and Kaye(3), Tables 4 and 7 respectively, for the given T_{BO}.

<u>Percent Theoretical Air for Combustion of JP4R Fuel.</u>

JP4R is basically a $(C\ H_2)n$ type fuel with a lower heating value of 18,600 BTU/Lb and a stoichiometric fuel-air ratio of 0.067.

Substituting in equation (6) yields:

$$\%\ AIR_y = \left[\frac{124,500}{\dfrac{H_{BO_x}}{MW_x} - h_{BI}}\right] - 6.7 \tag{9}$$

APPENDIX B (Cont'd)

Total Burner Air Flow.

From equation (5)

$$W_{aBI} = \left(\frac{\%\ AIR_y}{6.7}\right)(W_{fB}) \tag{10}$$

Now, by combining equations (7), (8), (9) and (10) in an iterative process the total burner air flow can be calculated in the following manner:

Knowing T_{BI} and T_{BO} determine values for h_{BI}, $H_{BO(400)}$ and $H_{BO(200)}$ from Keenan and Kaye(3).

For the first calculation, assume % AIR_x = 400% and calculate % AIR_y using equation (9), with H_{BI}, $H_{BO(400)}$ and M.W. for 400% air calculated by equation (7).

Compare the value obtained for % AIR_y with the initial assumed value of 400% AIR.

If % AIR_y does not agree with % AIR_x to within 10%, substitute the value of % AIR_y for % AIR_x and repeat the above process using equation (7) to calculate $M.W._x$, equation (8) to determine H_{BO_x} and equation (9) to obtain a new value for % AIR_y.

When % AIR_y agrees within 10% with % AIR_x, calculate total Burner Air Flow (W_{aBI}) using equation (10).

Example:

The following conditions are given:

T_{BI} = 43°F = 503°R $\qquad$ T_{BD} = 1125°F = 1585°R

W_{fB} = 664.2 Lb/Hr = 0.1845 Lb/Sec (JP4R)

APPENDIX B (Cont'd)

From Keenan and Kaye[3]:

Table 1 - h_{BI} = 120.20 BTU/Lb

Table 4 - $H_{BO(400)}$ = 11546.5 BTU/Mole

Table 7 - $H_{BO(200)}$ = 11737.6 BTU/Mole

Assume % AIR_x = 400%

From equation (7):

$$M.W._{(400)} = 28.924 + 0.000075\ (400) = 28.954$$

Using equation (9):

$$\%\ AIR_y = \frac{124{,}500}{\left[\frac{11546.5}{28.954} - 120.20\right]} - 6.7 = 440\%$$

Now, (% AIR_y - % AIR_x) > 10%

Therefore, let % AIR_x = % AIR_y = 440% and repeat.

From equation (7):

$$M.W._{(440)} = 28.924 + 0.000075\ (440) = 28.957$$

Equation (8) yields:

$$H_{BO(440)} = 11546.5 - \left[\frac{11737.6 - 11546.5}{200}\right] (440-400)$$

$$H_{BO(440)} = 11508.3 \text{ BTU/Mole}$$

Using equation (9):

$$\%\ AIR_y = \frac{124{,}500}{\left[\frac{11508.3}{28.957} - 120.20\right]} - 6.7 = 443\%$$

APPENDIX B (Cont'd)

Now; (% AIR_y - % AIR_x) = (443 - 440) = 3% which is less than 10%.

Therefore, using equation (10):

$$W_{aBI} = \left[\frac{443}{6.7}\right] (0.1845) = 12.199 \text{ Lb/Sec}$$

Or, the total air flow through the direct combustion air heater for the given inlet, outlet and fuel flow conditions is 12.2 Lb/Sec.

Results from this approximation method for determining burner air flow were compared with values obtained when the methods of NACA TN 2071(4) were employed. For the range of air flows considered in this study, the approximation results agreed within 1% with the more precise values of TN 2071. As an illustration, air flow for the previous example calculated by the method of TN 2071 equals 12.15 Lb/Sec.

METHOD FOR DETERMINING PORTION OF DIRECT COMBUSTION AIR HEATER GASES WHICH ARE MIXED WITH PURE AIR TO FORM VITIATED ENGINE INLET AIR

To determine the quantity of hot combustion products which are mixed with pure air to attain a given desired engine inlet temperature, a basic heat balance equation is utilized.

$$W_{aC} \; C_{pC} \; \Delta T_C = W_{aBD} \; C_{pBD} \; \Delta T_{BD} \tag{11}$$

Since engine air flow (W_{aE}) = sum of the heat exchanger air flow (W_{aC}) and a portion of the burner gas flow (W_{aBD}); then:

$$W_{aC} = W_{aE} - W_{aBD}$$

The temperature change (ΔT_C) experienced by W_{aC} is the difference between the engine inlet temperature (T_{T_1}) and the heat exchanger discharge temperature (T_C), or:

$$\Delta T_C = (T_{T_1} - T_C)$$

APPENDIX B (Cont'd)

Similarly, (ΔT_{BD}) is the temperature change of the combustion products (W_{aBD}) and equals the difference between the temperature of (W_{aBD}) at the mixing point (T_{BD}) and at the engine inlet temperature (T_{T1});

$$\Delta T_{BD} = (T_{BD} - T_{T1})$$

Substituting these expressions in equation (11) yields:

$$(W_{aE} - W_{aBD}) \left[C_{pC} (T_{T1} - T_C) \right] = W_{aBD} \left[C_{pBD} (T_{BD} - T_{T1}) \right]$$

Solving for W_{aBD}:

$$W_{aBD} = \frac{W_{aE}}{1 + \dfrac{C_{pBD} (T_{BD} - T_{T1})}{C_{pC} (T_{T1} - T_C)}} \qquad (12)$$

The test data provides values for W_{aE}, T_{T1}, T_{BD} and T_C. Knowing T_{BD} and T_C, values for C_{pBD} and C_{pC} are determined from Keenan and Kaye$_{(3)}$, Table 5 and Table 2 respectively.

<u>Example</u>:

The following conditions are given:

W_{aE} = 45.0 Lb/Sec

T_{T1} = 100°F = 560°R

T_{BD} = 1040°F = 1500°R

T_C = -60°F = 400°R

From Keenan and Kaye$_{(3)}$:

Table 5 C_{pBD} = 7.852 BTU/Lb-Mole °F [Fuel type - $(CH_2)n$]

Table 2 C_{pC} = 0.2393 BTU/Lb - °F

APPENDIX B (Cont'd)

Now; $C_{pBD} = \frac{7.852 \text{ BTU/Lb-Mole °F}}{28.954} = 0.2712 \text{ BTU/Lb - °F}$

Substituting in equation (12):

$$W_{aBD} = \frac{45.0}{1 + \frac{0.2712\ (1500-560)}{0.2393\ (560-400)}} = 5.88 \text{ Lb/Sec}$$

METHOD FOR DETERMINING PERCENT VITIATION

Percent vitiation (% vit) will be defined as the percent of oxygen removed or displaced in pure air by the addition of diluents or by a chemical reaction such as combustion. In other words, air which is 0% vitiated has the standard oxygen content of 23%. Conversely, air which is 100% vitiated contains no oxygen at all.

The amount of oxygen removed from air as the result of a combustion process is directly proportional to the actual fuel-air ratio divided by the stoichiometric fuel-air ratio, assuming of course that complete combustion takes place. Therefore, the theoretical oxygen remaining in the air heater combustion products which are to be mixed with the pure air is:

$$W_{(O_2)BD} = (W_{aBD})\ (0.23) - W_{aBD}\ (0.23) \left| \frac{W_{fB} / W_{aBI}}{F/A \text{ stoic.}} \right|$$

Simplifying:

$$W_{(O_2)BD} = W_{aBD}\ (0.23) \left[1 - \frac{W_{fb}/W_{aBI}}{F/A \text{ stoic.}} \right] \qquad (13)$$

The oxygen in the engine inlet air flow is contributed by the heat exchanger flow (W_{aC}) and the mixing gas flow (W_{aBD}) from the burner. Since W_{aC} is pure air, its oxygen content will be:

$$W_{(O_2)C} = (0.23)\ W_{aC} \qquad (14)$$

Combining equations (13) and (14) yields an expression for the oxygen content of the engine inlet air flow ($W_{(O_2)E}$):

$$W_{(O_2)E} = 0.23 \ W_{aC} + 0.23 \ W_{aBD} \left[1 - \frac{W_{fB} / W_{aBI}}{F/A \text{ stoic.}} \right] \qquad (15)$$

By definition then, the percent vitiation of (W_{aE}) is:

$$\% \text{ vit} = \frac{0.23 \ W_{aE} - W_{(O_2)E}}{0.23 \ W_{aE}} \times 100$$

Substituting expression (15) for $W_{(O_2)E}$ gives:

$$\% \text{ vit} = \frac{0.23 \ W_{aE} - 0.23 \ W_{aC} - 0.23 \ W_{aBD} + 0.23 \ W_{aBD} \dfrac{W_{fB} / W_{aBI}}{F/A \text{ stoic.}}}{0.23 \ W_{aE}} \times 100$$

Simplifying:

$$\% \text{ vit} = \frac{W_{aE} - (W_{aC} + W_{aBD}) + W_{aBD} \dfrac{W_{fB} / W_{aBI}}{F/A \text{ stoic.}}}{W_{aE}} \times 100$$

But: $W_{aC} + W_{aBD} = W_{aE}$

Therefore:

$$\% \text{ vit} = \frac{W_{aBD} \ W_{fB}}{W_{aE} \ W_{aBI} \ F/A \text{ stoic.}} \times 100 \qquad (16)$$

Since all terms in expression (16) are known or can be calculated, the percent vitiation for a given test condition may be determined.

<u>Example</u>:

From previous examples:

$W_{fB} = 0.1845$ Lb/Sec, $W_{aBI} = 12.2$ Lb/Sec

$W_{aE} = 45.0$ Lb/Sec, $W_{aBD} = 5.88$ Lb/Sec

F/A stoic. (JP4R) = 0.067

or: $$\% \text{ vit} = \frac{(5.88) \ (0.1845)}{(45.0) \ (12.2) \ (0.067)} \times 100 = 2.94\%$$

TABLE I

INSTRUMENTATION SCHEDULE

Parameter	Number & Type	Recorder	Range	Units	Accuracy
T_{T1}	5 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
T_{T3}	3 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
T_{fE}	1 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
$T_{ENG\ OIL}$	1 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
T_{fB}	1 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
T_{T2}	5 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
T_{TBI}	1 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
T_{TC}	1 I.C.	Brown Precision Indicator	-65 to 400	°F	±1% F.S.
T_{TBO}	1 C.A.	Brown Precision Indicator	0-2000	°F	±0.5% F.S.
T_{TBD}	1 C.A.	Brown Precision Indicator	0-2000	°F	±0.5% F.S.
T_{T5}	3 C.A.	Brown Precision Indicator	0-2000	°F	±0.5% F.S.
T_{T5} average		Vertical Scale Indicator	0-2000	°F	±0.75% F.S.
W_{fE}	2 ½" Flowmeter	Electronic Counter	0-2000	CPS	±0.25% F.S.
W_{fB}	1 ½" Flowmeter	Electronic Counter	0-2000	CPS	±0.25% F.S.
P_{T1}	9 Finger Rake	Mercury Manometer	0-100	"Hg	±0.15"Hg
P_{S1}	2 Wall Static	Mercury Manometer	0-100	"Hg	±0.15"Hg

TABLE I - INSTRUMENTATION SCHEDULE (Cont'd)

Parameter	Number & Type	Recorder	Range	Units	Accuracy
P_{T2}	5 Finger Rake	Mercury Manometer	0-100	"Hg	$\pm$0.15"Hg
P_{S2}	2 Wall Static	Mercury Manometer	0-100	"Hg	$\pm$0.15"Hg
P_{S9}	1 Lip Static	Mercury Manometer	0-100	"Hg	$\pm$0.15"Hg
P_{TBD}	1 Pitot	Mercury Manometer	0-100	"Hg	$\pm$0.15"Hg
P_{TB1}	1 Pitot	Mercury Manometer	0-100	"Hg	$\pm$0.15"Hg
P_{T1}	Tee to Above	Dibutyl U-Tube	0-100	"DB	$\pm$0.15"DB
P_{S1}	Tee to Above	Dibutyl U-Tube	0-100	"DB	$\pm$0.15"DB
N	1 ILS 120	Electronic Counter	0-8400	CPS	$\pm$0.15% F.S.
P_{S3}	1 Fuel Control Press. Port.	Kollsman Gage	0-400	"HgA	$\pm$1.5"Hg
P_{T5} average	4 Engine Harness	Kollsman Gage	0-400	"HgA	$\pm$1.5"Hg

TABLE II

OSCILLOGRAPH INSTRUMENTATION CHARACTERISTICS

Parameter	Channel Number	Range	Units	Recording Accuracy	Reading Resolution
PLP	1	0-95	Degrees (Angular)	$\pm$ 2	0.3°
N	2	0-8400	CPS	$\pm$ 42	27 CPS
W_{fE}	3	0-2000	CPS	$\pm$ 10	6.5 CPS
P_{S1}	4	0-30	psia	$\pm$ 0.3	0.05 psia
P_{T1}	5	0-50	psia	$\pm$ 0.5	0.1 psia
P_{S9}	6	0-30	psia	$\pm$ 0.3	0.05 psia
P_{T5}	7	0-50	psia	$\pm$ 0.5	0.1 psia
T_{T5}	8	0-40	MV	Averaged Reading	0.01 MV
P_{S3}	9	0-150	psia	$\pm$ 1.5	0.5 psia

TABLE III

TEST DATA AND RUN INDEX

Mach Number	Inlet Total Pressure ("HgA)	Inlet Total Temperature (°F)	Nominal Percent Vitiation	Run Nos.
0.0	29.9	60	0.0	01-06
0.0	29.9	103	0.0	07-11
			1.7	61-66
			2.3	26-31
			3.0	34-39
0.5	35.2	132	0.0	12-16
			2.3	55-60
			3.0	21-25
			3.5	40-45
0.85	48.2	185	0.0	17-20
			2.3	67-71
			3.0	50-54
			3.5	32-33, 46-49

FIGURE 1: VITIATED AIR STUDY - TEST FACILITY SCHEMATIC, 3W TEST CELL

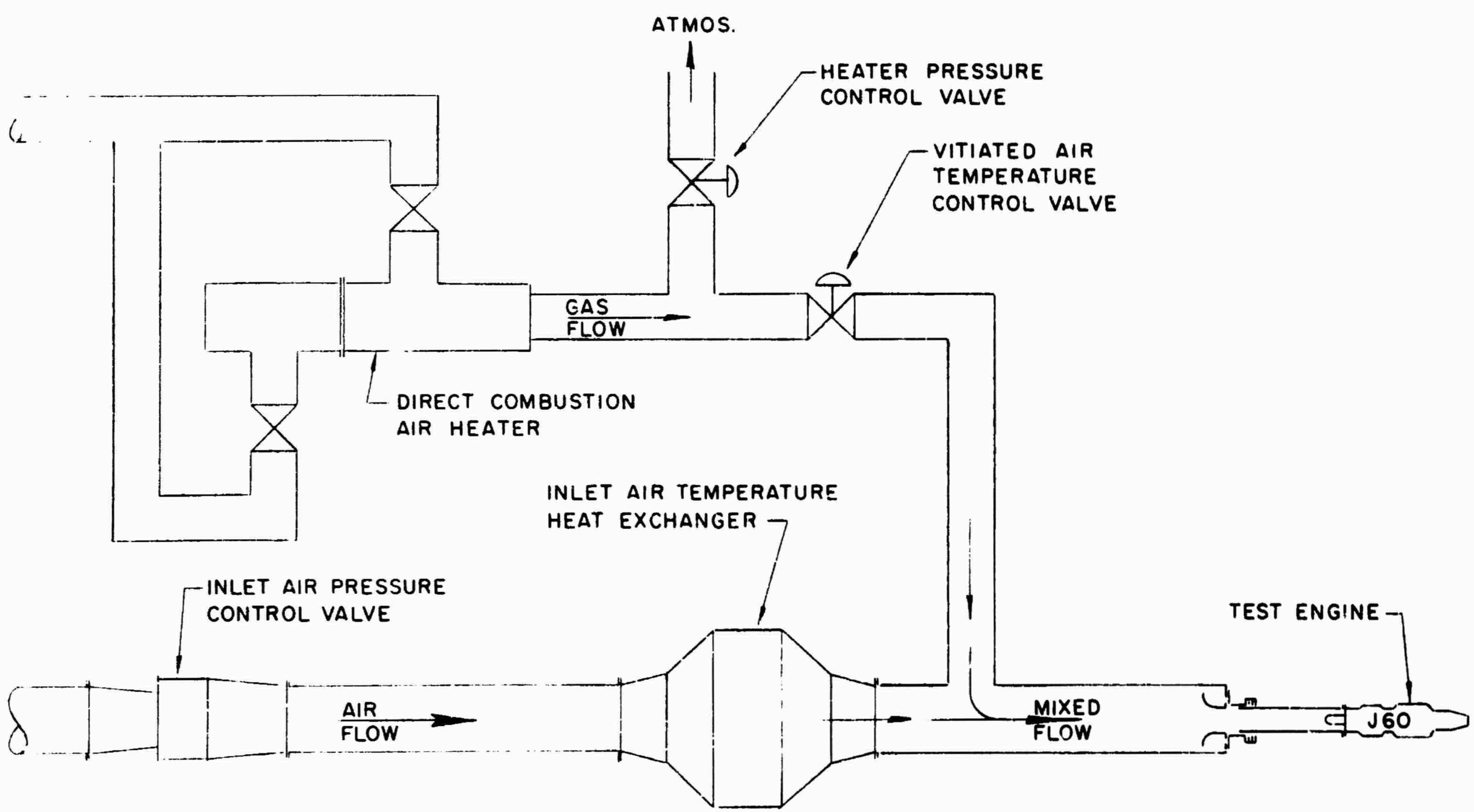
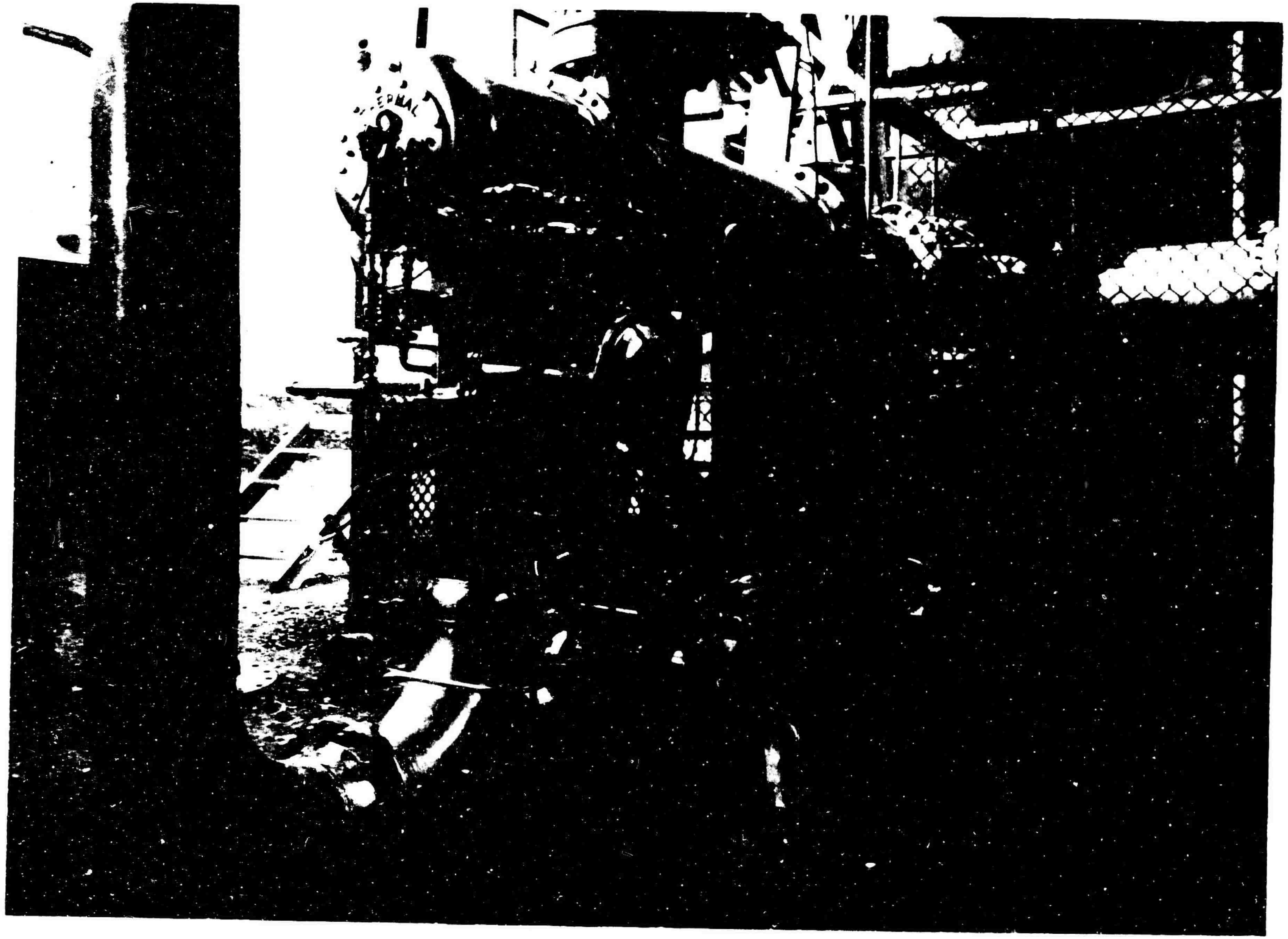


FIGURE 2: DIRECT COMBUSTION AIR HEATER



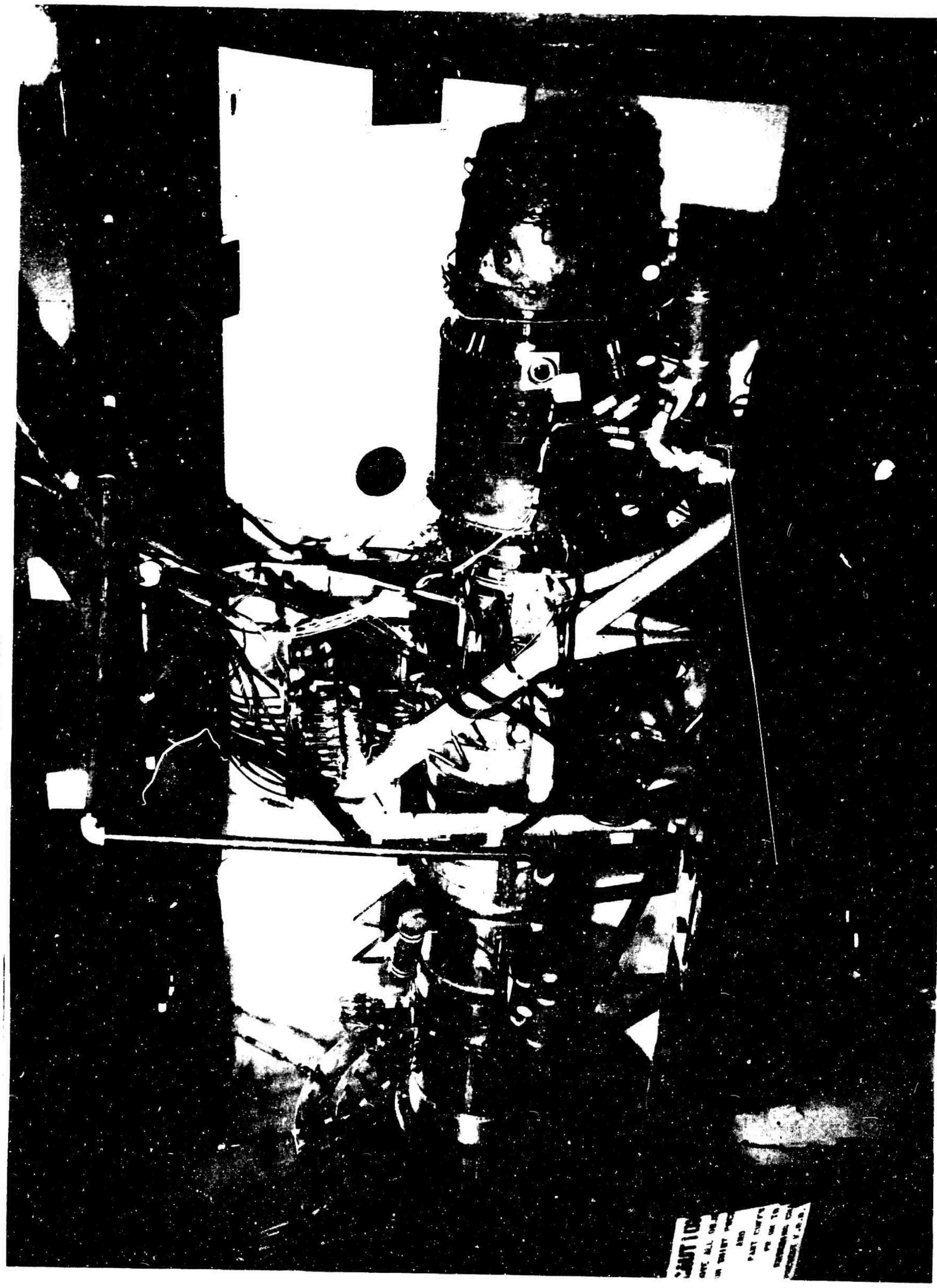


FIGURE [illegible] ENGINE INSTALLATION [illegible] TEST CELL

FIGURE 4: VITIATED AIR TEST - INSTRUMENTATION DIAGRAM

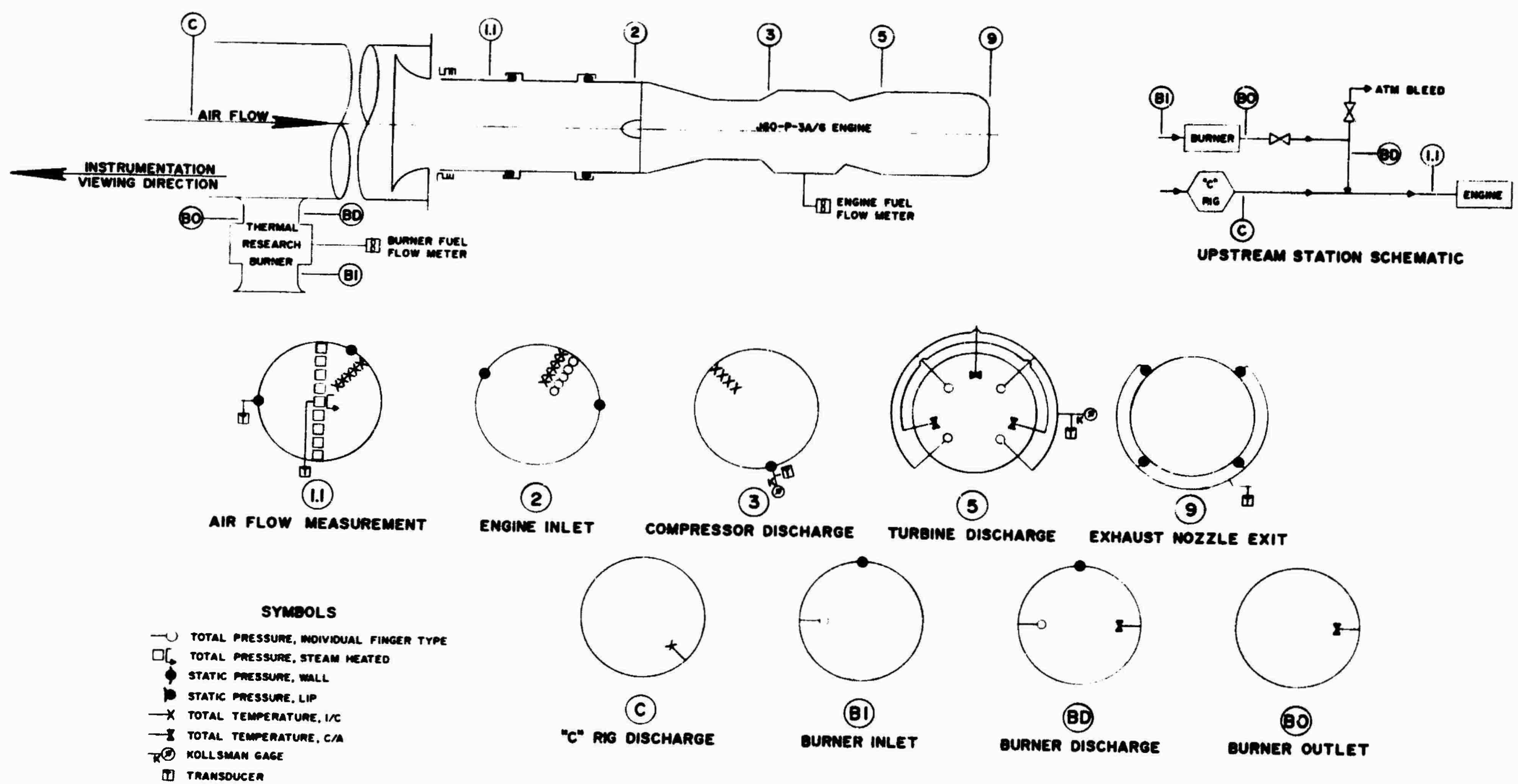


FIGURE 5: EFFECT OF VITIATION ON COMPRESSOR PRESSURE RATIO

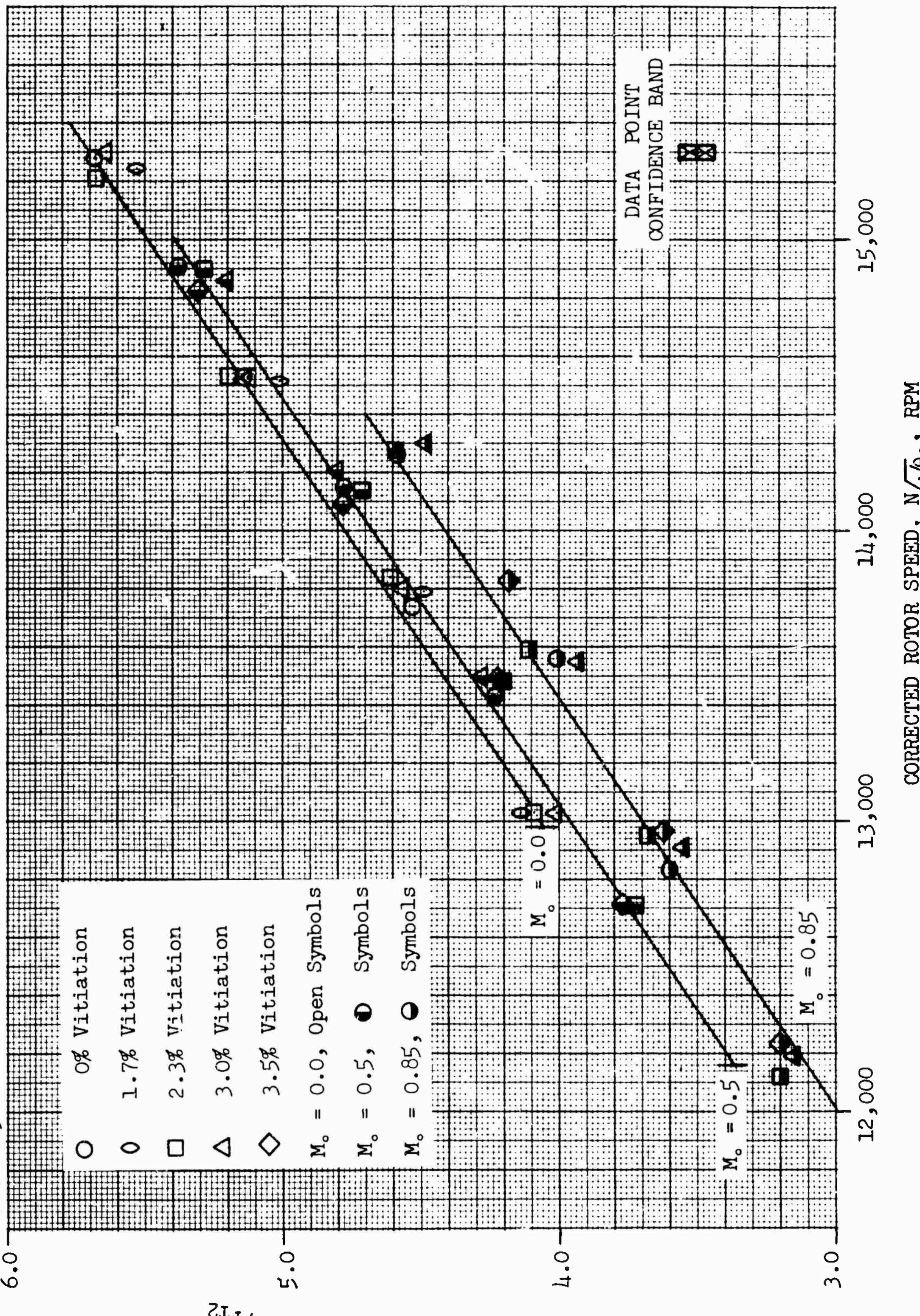


FIGURE 6: EFFECT OF VITIATION ON TURBINE DISCHARGE TEMPERATURE

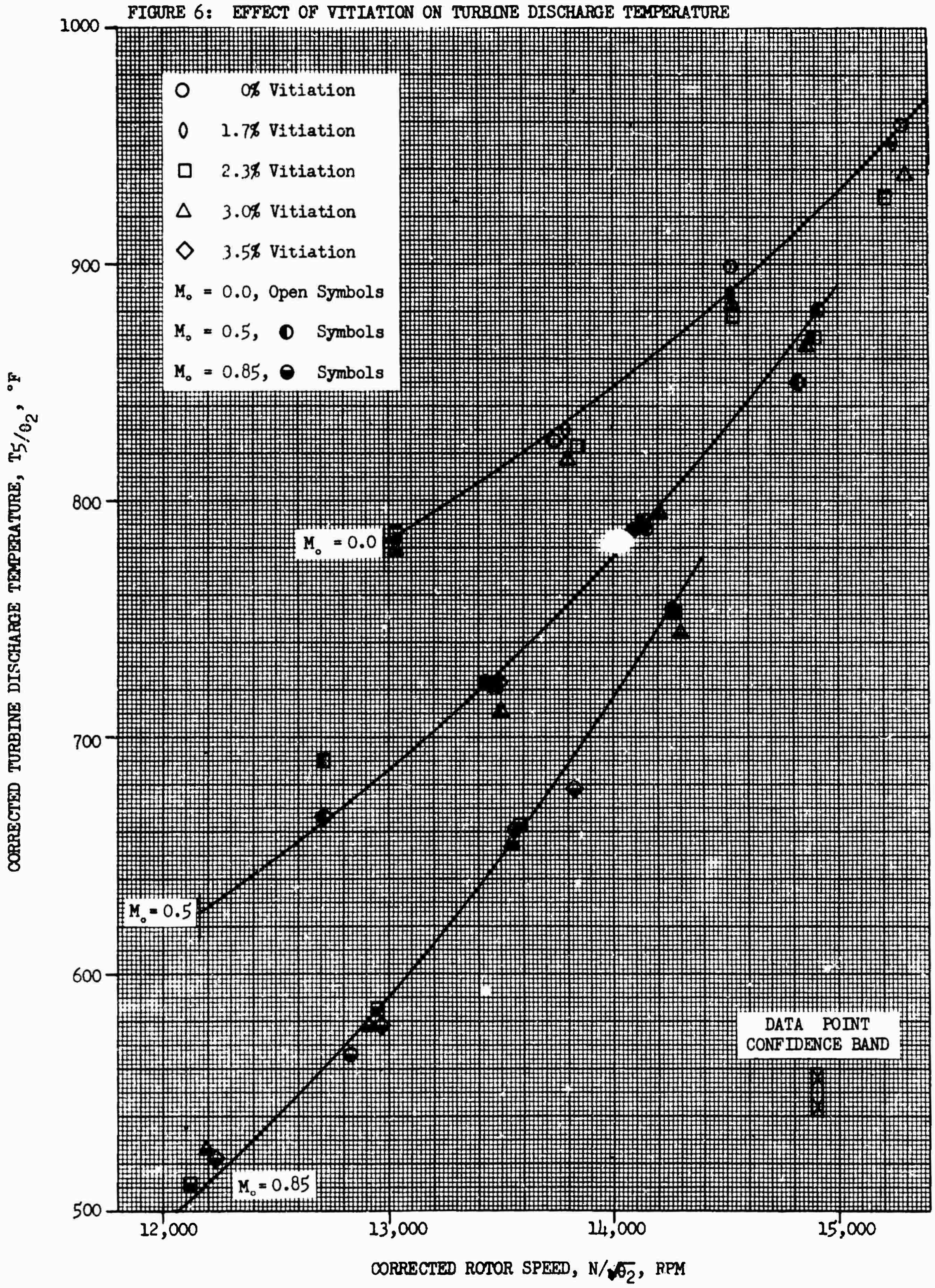


FIGURE 7: EFFECT OF VITIATION ON FUEL CONTROL PARAMETER

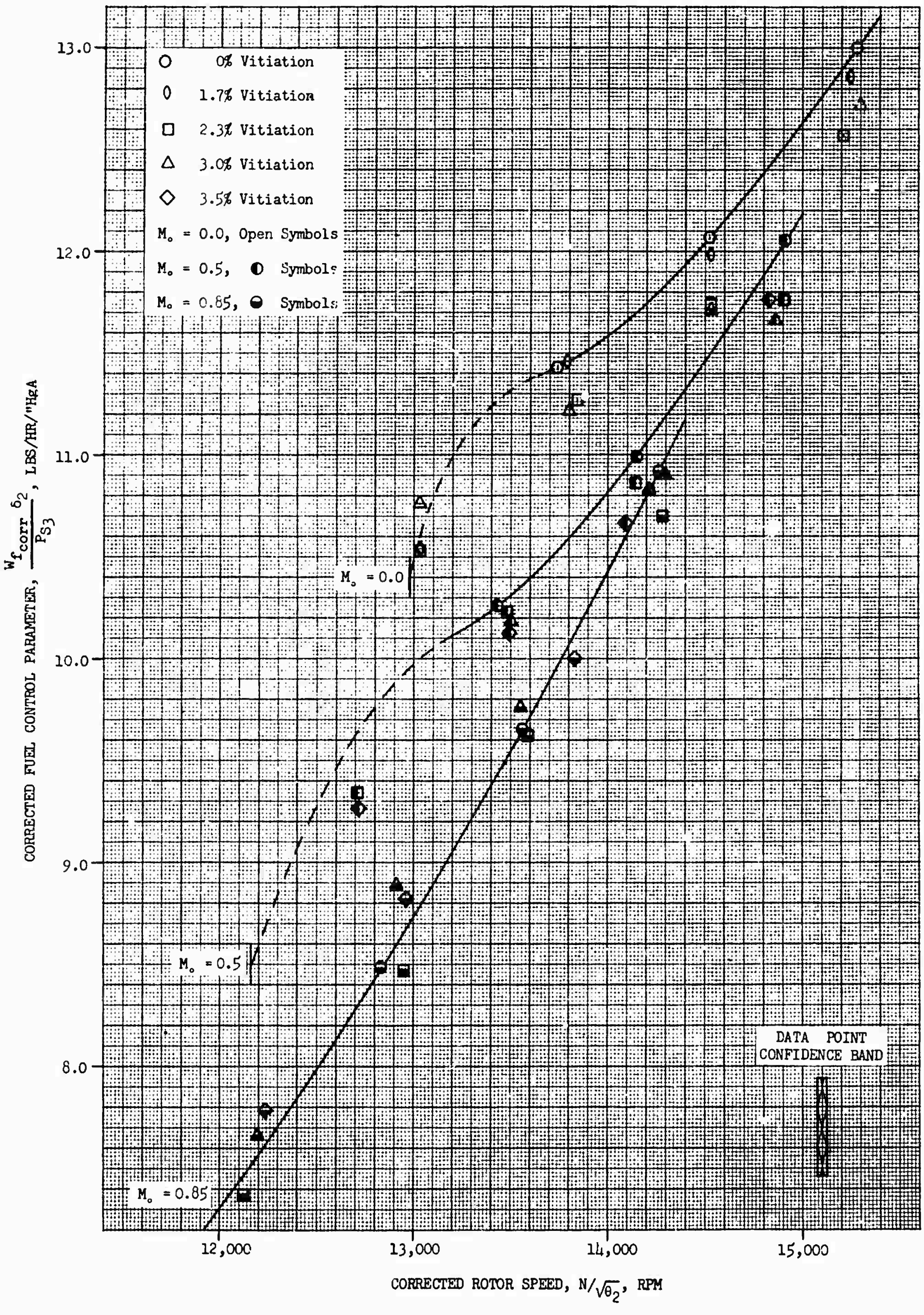
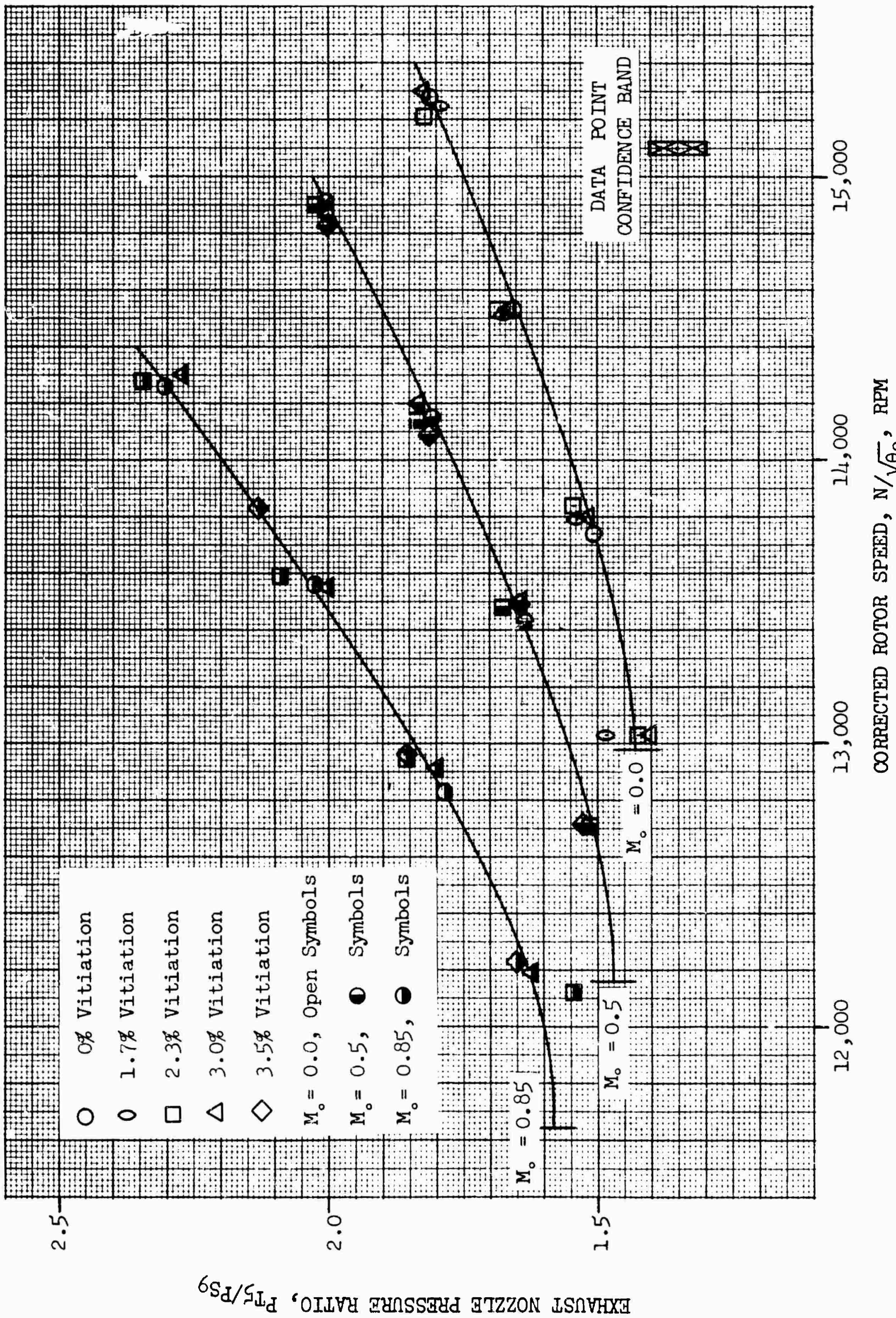


FIGURE 8: EFFECT OF VITIATION ON EXHAUST NOZZLE PRESSURE RATIO



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13. ABSTRACT

Laboratory tests were conducted to investigate the effects of vitiated inlet-air on turbojet engine performance. The test vehicle was a J60-P-6 turbojet engine which was operated at sea level hot day inlet conditions for simulated flight Mach numbers of 0.0, 0.5, and 0.85. Effects of vitiated inlet-air were evaluated at vitiation levels of 1.7, 2.3, 3.0, and 3.5 percent.

In general, inlet-air vitiation levels, up to 3.5%, created no measurable effects on engine performance.

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